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On-Orbit Results from the CanX-7 Drag Sail Deorbit Mission

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ABSTRACT

As a proactive solution to the orbital debris problem, the Space Flight Laboratory (SFL) has developed a passive drag sail deorbit device to remove small satellites from low-Earth orbit (LEO). Upon end-of-mission, the drag sail can be deployed to decrease the ballistic coefficient of the host spacecraft. Without any further operator intervention, the drag sail will interact with Earth's upper atmosphere to decrease the spacecraft's orbital energy causing it to eventually deorbit. In order to demonstrate the drag sail technology on-orbit, it has been included as the primary payload on-board the CanX-7 mission, which was launched in September 2016. After successfully completing a seven-month aircraft tracking campaign using the CanX-7 ADS-B payload, the drag sails were deployed in May 2017. This paper provides a first look at the on-orbit results from the CanX-7 mission, focusing on the performance of SFL's drag sail device.

INTRODUCTION

In recent years, orbital debris has been identified as a major risk to the future of space operations. Every satellite on-orbit is susceptible to collision with orbital debris, which is likely to result in loss of mission. If satellites continue to be sent into orbit without implementing any means of space debris mitigation, the probability of collisions will increase, and eventually, carrying out useful space operations will become impossible. In an effort to maintain current satellite operations and protect the future of space technology, the Inter-Agency Space Debris Coordination Committee (IADC) has developed a guideline that all LEO satellites should have a means to deorbit within 25 years of end-of-mission [1].

Deorbiting is particularly challenging for micro and nanosatellites, as they are limited in terms of mass and volume. With regulatory bodies around the world beginning to enforce the IADC deorbit guidelines, this represents a major roadblock for the small satellite community. To avoid these roadblocks for future operational missions, the CanX-7 mission was conceived in order to develop a deorbit device for small satellites in LEO and demonstrate it on-orbit.

During the early stages of the CanX-7 mission, a drag sail was chosen as the most promising deorbit technology for small satellites [2]. A drag sail deorbit device is completely passive, compact, lightweight, and scalable; and does not require any propellants or pressurants. Through many design iterations and rigorous testing, a flight qualified drag sail device was developed. This technology has now been successfully demonstrated on-orbit., therefore allowing it to be included on future operational missions.

In the subsequent sections, more details regarding the CanX-7 mission and SFL's drag sail deorbit device will be provided. Following this, a first look at the on-orbit results for the drag sail device are presented. In particular, a comparison between the expected and actual deorbit performance of the spacecraft is provided. With the design of the drag sail device validated, the second part of the paper focuses on future mission planning, with emphasis on how the device could be accommodated on a variety of spacecraft platforms of varying size.

CANX-7 MISSION

CanX-7 (Canadian Advanced Nanospace eXperiment-7) is a technology demonstration mission designed to demonstrate two payloads in LEO. The primary payload is the drag sail deorbit device, and the secondary payload is an Automatic Dependent Surveillance-Broadcast (ADS-B) receiver for tracking aircraft. CanX-7 was launched into a 680 km SSO on September 26, 2016 as a secondary payload on-board PSLV-C35.

For seven months following spacecraft commissioning, the CanX-7 spacecraft completed an aircraft tracking campaign. During this period over 4.5 million ADS-B messages were received and decoded by the ADS-B payload [3]. On its own, successful demonstration of the ADS-B payload on-orbit is a significant accomplishment, as this same technology could form the basis for a constellation of satellites for global, realtime aircraft tracking. In the context of the drag sail demonstration, the ADS-B payload is also very useful. By deploying the drag sail following the ADS-B payload demonstration, the mission profile resembles that of an operational mission where the spacecraft would carry out regular operations for months or years prior to initiating deorbiting. A key component in the drag sail technology demonstration was long-term stowage of the drag sail in space without interrupting or affecting the operational mission.

On May 4, 2017 the drag sail was deployed, kicking off the deorbit portion of the CanX-7 mission. The deployment was verified using on-board telemetry as well as ground based sensors. For the duration of deorbiting, spacecraft telemetry will be used to determine the spacecraft attitude and orbit information from JSpOC will be used to monitor the deorbit profile. Changes in ballistic coefficient and orbit decay rate were apparent within the first week after sail deployment, indicating that the drag sail is functioning as expected.

CanX-7 Spacecraft

The CanX-7 spacecraft has a mass of 3.6 kg and dimensions of 10 x 10 x 34 cm. A photo of the spacecraft can be seen in Figure 1. The drag sail modules are located at one end of the spacecraft, and comprise less than 25% of the spacecraft volume. With the plane of the drag sail offset from the spacecraft's center of mass, a favorable aero-stable attitude (providing optimal drag area) is more likely to persist.

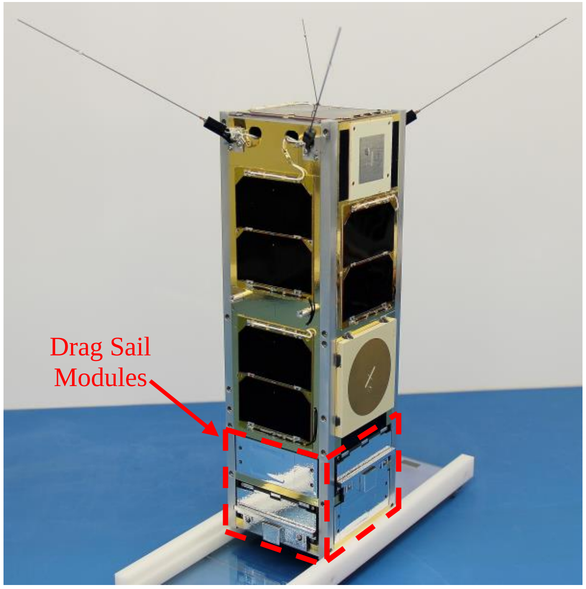

Figure 1: CanX-7 Spacecraft in Cleanroom Prior to Launch

The spacecraft design is based on SFL's CanX-2 bus (similar to a 3U cubesat), and all subsystems are comprised of SFL hardware. CanX-7 uses the SFL Modular Power System (MPS) for power conditioning and distribution. A single SFL On-Board Computer (OBC) handles all commands, telemetry gathering, attitude control, and payload interfaces. A UHF receiver along with a canted turnstile antenna allows for radio uplink, and a S-band transmitter along with two patch antennas allows for radio downlink. An entirely magnetic attitude determination and control solution is implemented with a magnetometer and a set of three orthogonally mounted magnetorquers. The attitude control system was used to support ADS-B payload operations and is not intended for use during deorbiting.

The ADS-B payload was developed in collaboration with the Royal Military College of Canada (RMCC). It consists of a commercial-off-the-shelf receiver, modified for use in space, and a custom designed circularly polarized patch antenna.

DRAG SAIL DEORBIT DEVICE

The CanX-7 deorbit device deploys a thin film sail membrane that provides a total drag area of 4 m^2. The sail design is unique in that it is modular [4]. The sail is made up of four individual modules that each deploy a 1 m^2 portion of the sail. Figure 2 provides a photo of a single drag sail module in the stowed configuration. The sail sections are mechanically deployed using tape spring booms, which also maintain the sail geometry post-deployment. Each sail module is equipped with a deployment mechanism and electronics for command and telemetry gathering. This allows the sail modules to be operated independently of one another to protect against a single point of failure. In addition to redundancy, the modular design allows the deorbit device to be adapted for different spacecraft geometries and drag area requirements.

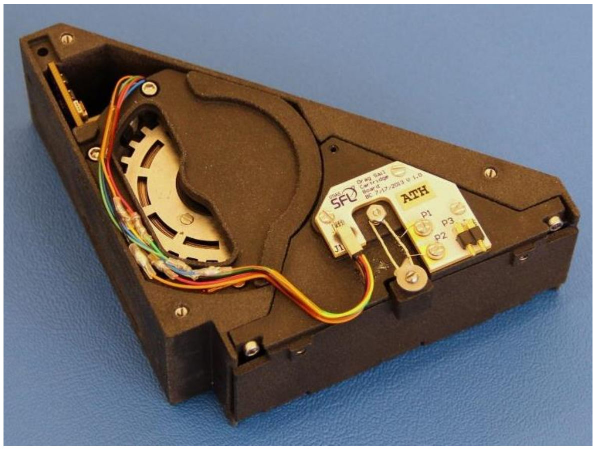

Figure 2: Single Drag Sail Module

Each drag sail module has a mass of 200 g and its dimensions are 10 x 10 x 3 cm (base x height x thickness). The module structure is additively manufactured using a carbon fiber reinforced polyamide composite material. This allows for a lightweight product with intricate features that would be difficult to make using traditional machining. The sail membrane is made from a double aluminized polyimide material. This thin film material is lightweight and flexible, allowing it to be folded and stowed in a small cartridge that fits inside the sail module. The material also provides the mechanical and thermal properties required to allow the sail to survive the harsh space environment for up to 25 years. The tape spring booms are custom manufactured to allow for full control over spring stiffness and mounting geometry. The booms are made from a copper beryllium alloy to ensure magnetic cleanliness.

Each of the drag sail modules has its own electronics for command and telemetry gathering. Deployment commands are accepted directly from the UHF radio uplink, and a set of two commands (ARM and FIRE) must be received to trigger the deployment of each sail segment. When the ARM and FIRE commands are received in sequence, a heating element is activated to melt a Vectran® cord, thereby releasing a door on the sail cartridge. Once the door is released, the tape spring booms are free to unwind, and in the process the sail segment is unfurled.

The objective of the sail telemetry system is to collect enough information to detect full deployments (success), as well as partial deployments of the sail. This is accomplished with the use of a door switch and a reel sensor. The door switch forms a circuit that is monitored to determine the state of the cartridge door (open or closed). This telemetry indicates whether the door has been successfully released following activation of the heating element. The reel sensor consists of a Hall effect sensor that is used to count gear teeth on the reel flange. This allows the extent of boom deployment to be measured with a resolution of 4 mm (0.24% of the total boom length). In addition to determining the state of deployment, the reel sensor data is time-tagged, allowing velocity and acceleration profiles for the deployment to be plotted.

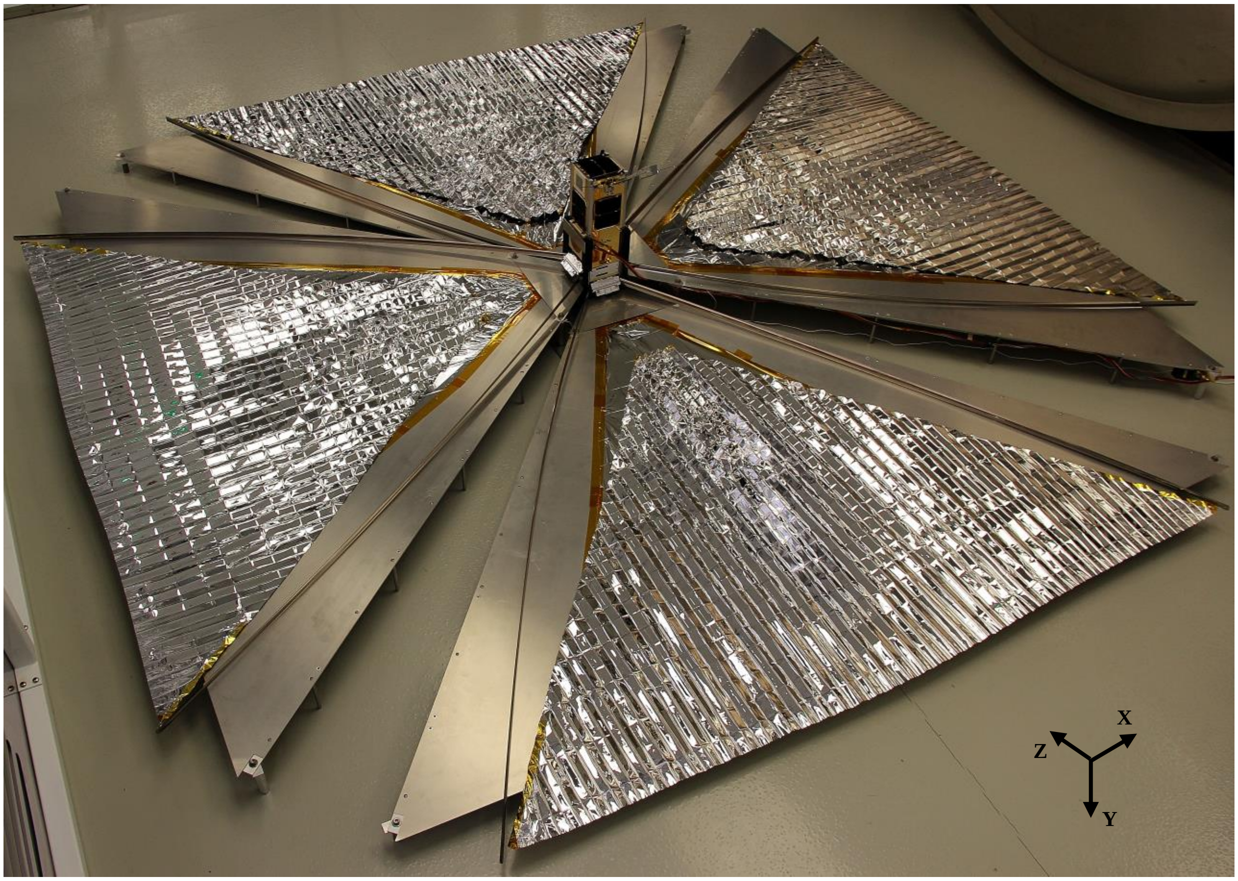

Figure 3: CanX-7 Spacecraft with Fully Deployed Drag Sail during Testing at SFL

ON-ORBIT RESULTS

At the time of writing, it has been just over one month since the CanX-7 drag sail was deployed. At this time, information related to the deployment event and early analysis of the deorbit profile can be presented. To fully verify sail performance, long-term monitoring of the spacecraft attitude and orbit is required. This information will be published once it becomes available.

Sail Deployment

All four drag sail segments were deployed on May 4, 2017. The sail segments were deployed across two orbits while the spacecraft was in radio contact with the mission control center in Toronto, Ontario. Specific deployment times for each sail segment are listed in Table 1. The sail segments are labeled according to their location in the spacecraft body-fixed frame (see Figure 3). Immediately after the deployment of each sail segment, telemetry was downloaded from the spacecraft. As discussed, the telemetry consists of a door switch status and a reel gear tooth count. Door switch telemetry indicates that all sail module doors were released between 3 and 4 seconds after receiving the FIRE commands. This timing is consistent with ground testing in vacuum and shows that the burn-cord release mechanism functioned correctly in space. The reel sensor telemetry was used to verify the deployment profiles, which can be seen in Figure 4. The gear tooth count provides an indication of deployment extent, with a count of 410 indicating 100% deployment. All deployments followed the expected nominal profile, with some variation caused by the unfolding process. The non-linearities in the profiles are expected and are the result of temporary "sticking" of sail sections as they unfold. The –Z sail segment was somewhat slow to unfold, but did fully deploy around the 30 second mark (off-scale in Figure 4). The observed profiles correlate well with ground tests performed in vacuum, and confirm successful operation of the sail modules following long-term storage in space.

Table 1: Drag Sail Deployment Times

	Time (UTC)
-Z Sail Segment	2017-05-04 01:22:36.54
+Z Sail Segment	2017-05-04 01:23:49.81
-X Sail Segment	2017-05-04 03:00:17.67
+X Sail Segment	2017-05-04 03:01:30.55

In addition to the on-board sensors, the deployment was also detected by external sensors. The deployment was observed by researchers at Defence Research and Development Canada (DRDC) and RMCC using ground based optical sensors. This observation was part of a stand-alone experiment with the goal of observing spacecraft articulations using Earth-based sensors. Photometry was used to measure changes in reflected sunlight from the spacecraft before, during, and after sail deployment. Due to the large change in surfaces area and high solar reflectivity of the sail material, the deployment of each segment resulted in a large increase in observed brightness. Overall, the photometry results provided a secondary confirmation of deployment.

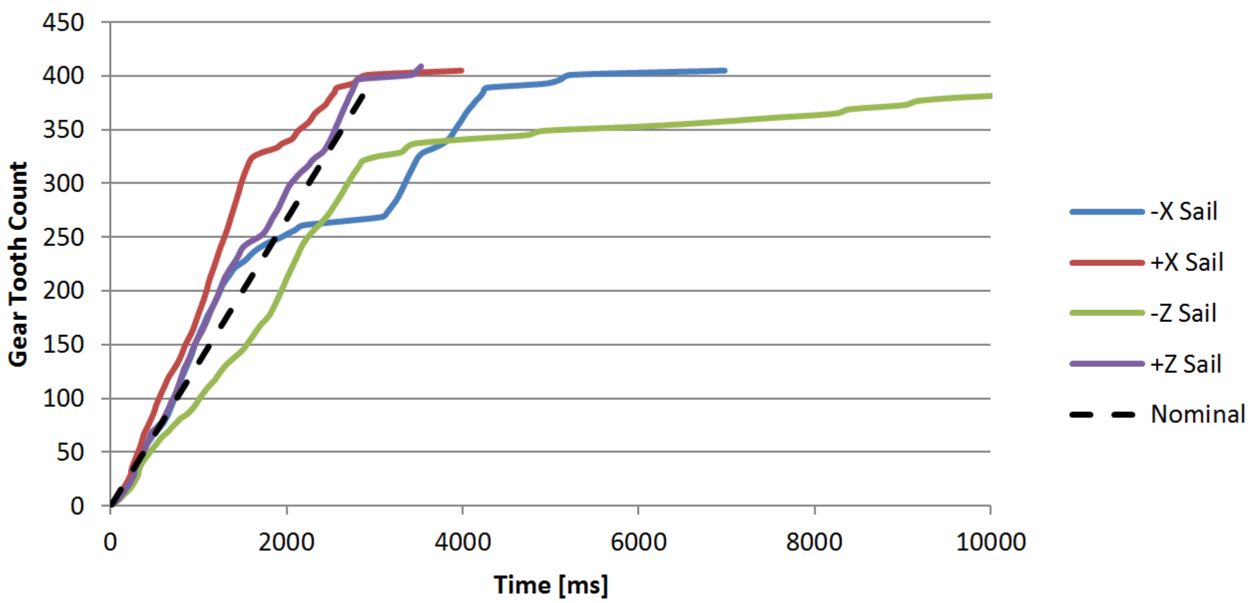

Figure 4: On-Orbit Deployment Profiles for the CanX-7 Drag Sail Modules

Deorbit Performance

A preliminary deorbit profile for the CanX-7 spacecraft is shown in Figure 5. The change in altitude decay rate upon deployment of the drag sail is very evident, increasing from about 0.5 km/year to 20 km/year. This decay rate only holds true for the near-term; as the altitude decreases, the atmospheric density increases exponentially and therefore so will the decay rate.

The actual deorbit profile is generated using information from Two-Line Element (TLE) sets provided by JPsOC. The expected profile is generated using *STK*'s lifetime analysis tool. For the expected profile, a drag coefficient of 2.2 is assumed, along with an effective drag area of 2 m^2. In addition, the *Jacchia 1970 Lifetime* atmospheric density model is used. The effective drag area of 2 m^2 is based on the attitude profile for the spacecraft during the month following deployment, during which the spacecraft was tumbling. The spacecraft tumbling is the result of disturbance torques acting on the spacecraft due to solar pressure, drag pressure, interactions with Earth's magnetic field, and interactions with Earth's gravity. These disturbances are amplified due to small variations in properties from sail segment to sail segment, including drag area, center of pressure, drag coefficient, and solar reflectivity. As the orbit altitude decreases, drag effects will begin to dominate the other disturbances forces and the spacecraft will begin to aero-stabilize, thereby increasing the effective drag area.

The difference between the actual and expected profiles is relatively small and can be accounted for by small errors in the expected drag coefficient or the drag area. Due to the unique nature in which the sail segments are folded and unfolded, the resulting surfaces have both small and large wrinkles. This makes it difficult to precisely predict the drag coefficient. The wrinkles also make it difficult to precisely estimate the projected drag area. Errors in the atmospheric density model could also account for the discrepancy.

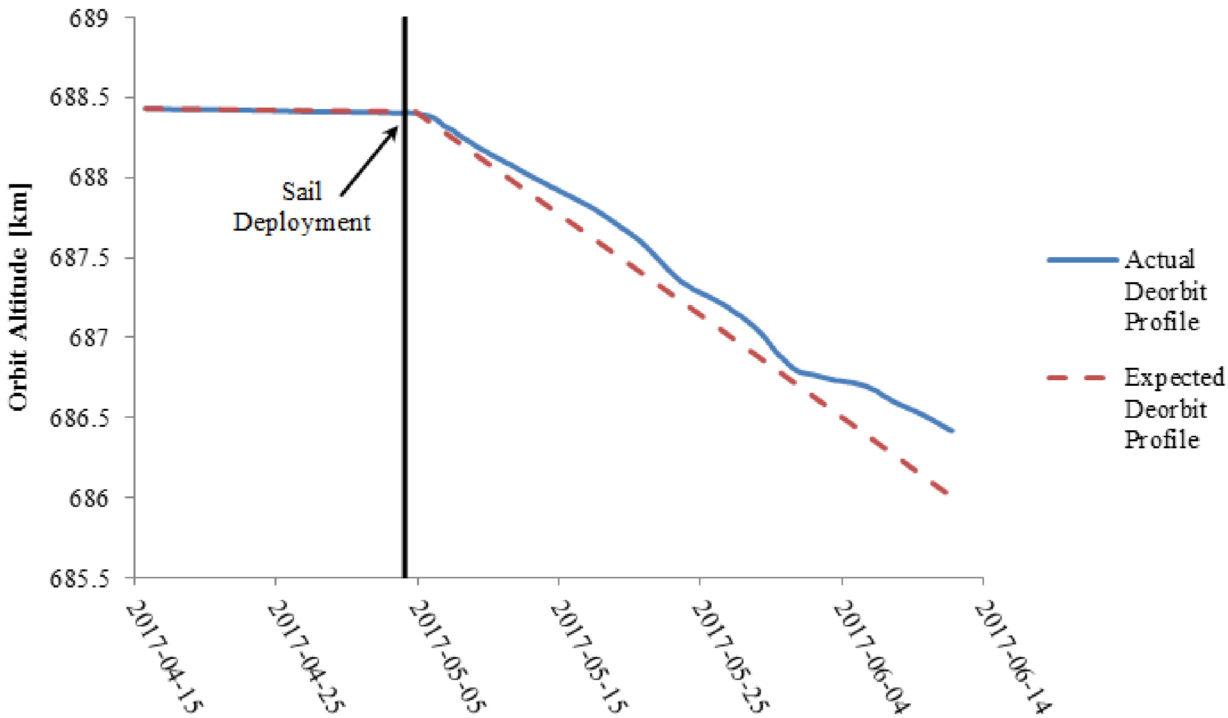

Figure 5: Preliminary Deorbit Profile for the CanX-7 Spacecraft

In addition to the change in decay rate, a significant change in spacecraft ballistic coefficient was observed. The ballistic coefficient is determined using information from TLE sets provided by JSpOC, and is plotted in Figure 6. Upon sail deployment, the ballistic coefficient decreased from an average value of 43 kg/m^2, to a value of 0.88 kg/m^2. Assuming a drag coefficient of 2.2, the post-deployment ballistic coefficient corresponds with an effective drag area of 1.85 m^2. This is close to the expected effective drag area given the spacecraft attitude profile.

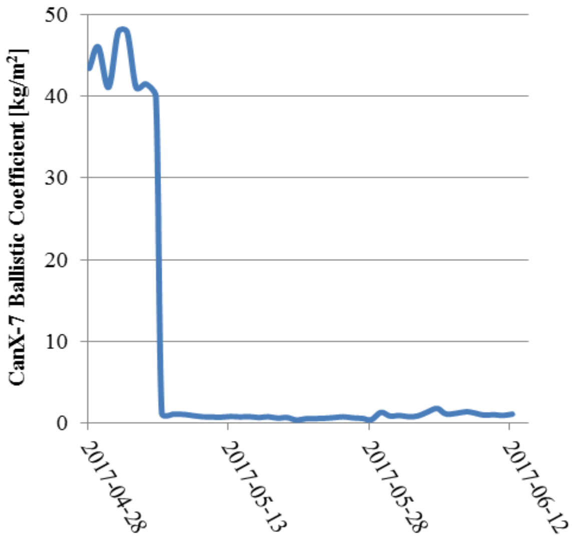

Figure 6: Ballistic Coefficient for CanX-7 before and after Sail Deployment

Even though the deorbit phase of the CanX-7 mission has only been underway for about one month, the data gathered so far has been used to update the deorbit predictions for the spacecraft. These updated predictions are summarized in Figure 7 below. First, it is important to note the expected lifetime of the spacecraft if it did not have any drag sails. Without drag sails, it is expected that the CanX-7 satellite would remain on-orbit for 178 years, far exceeding the IADC 25 year guideline. With the sails deployed, and assuming the current attitude profile resulting in an effective drag area of 2 m^2, the CanX-7 satellite would remain on-orbit for 4.5 years. This is a worst case scenario, as it is expected that the spacecraft will aero-stabilize as its altitude decreases. Due to the offset between the center-of-pressure of the sail segments and the center-of-mass for the spacecraft, CanX-7 benefits from the "shuttlecock" effect. This should cause the spacecraft to stabilize with the plane of drag sail perpendicular to the spacecraft velocity vector. At lower altitudes, the drag force will dominate over the other disturbance torques, allowing the aero-stabilized attitude to persist. Using the variable-attitude analysis approach for a passive drag sail equipped spacecraft presented in [5], the actual expected lifetime for the CanX-7 spacecraft – assuming aero-stabilization – is 2.9 years. All lifetime estimates are given from the time of sail deployment (May 4th, 2017).

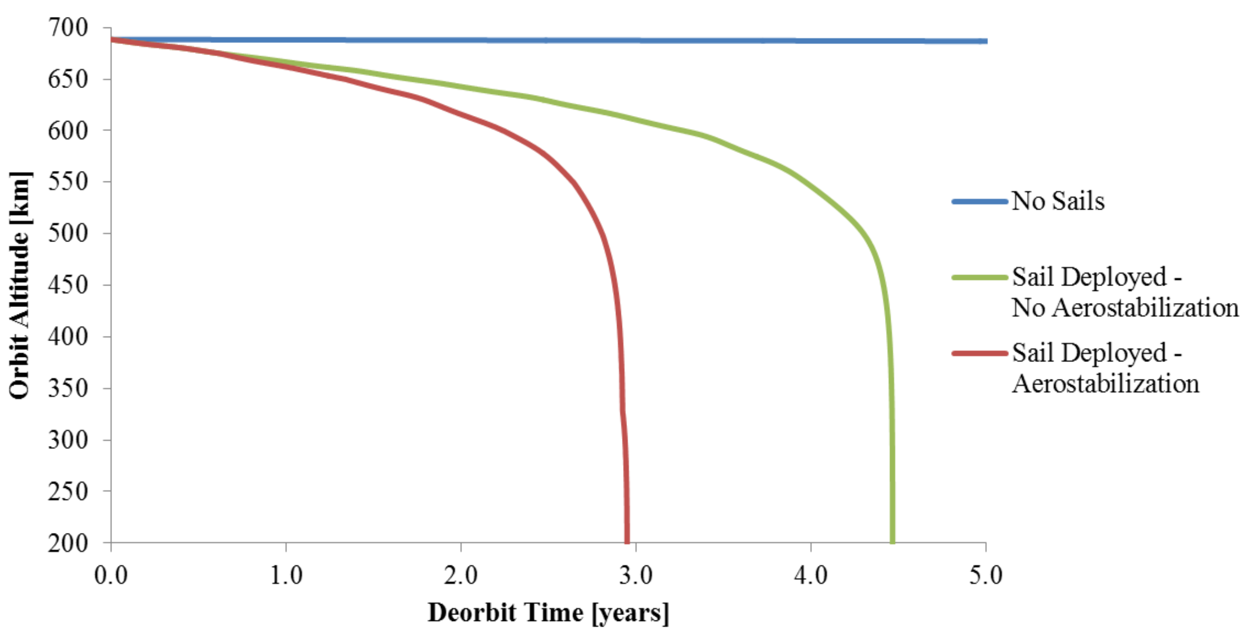

Figure 7: Predicted Long-Term Deorbit Performance for CanX-7

FUTURE APPLICATIONS

The drag sail deorbit device developed for the CanX-7 mission represents a proactive solution to the space debris problem, allowing micro and nanosatellites to be deorbited from LEO following mission completion. Initially, the drag sail was designed to deorbit a 15 kg spacecraft from up to 800 km while complying with IADC's 25 year deorbit guideline. However, due to the drag sail's lightweight, compact, and modular design, it can be integrated with a wide variety of small satellite platforms. Figure 8 below shows concept models of how the drag sail deorbit device could be integrated with various platforms including a double-cubesat (2U), SFL's Generic Nanosatellite Bus (GNB), and SFL's Next-generation Earth Monitoring and Observation (NEMO) bus.

The modular design allows the deorbit device to be adapted to almost any spacecraft geometry. It also allows the drag area to be tailored based on spacecraft mass and orbit altitude by choosing the number of modules that are used. For example, nanosatellites (less than 10 kg) would only require two sail modules to meet the deorbit guideline in most cases, whereas for microsatellites (greater than 10 kg) four or more modules would likely be required. In addition to scalability, the drag sail modules are designed to be minimally intrusive. Each module has a set of adaptable mounting features and a simple electrical interface. The sail modules do not impede the operational mission of a spacecraft. This is emphasized by the fact that the CanX-7 mission operated the ADS-B payload for seven months prior to deployment of the drag sail.

Figure 8 provides some specific examples of spacecraft geometries into which the drag sail could be incorporated. However, the possible applications are endless. As is, the drag sail device is suitable for satellites with masses ranging from 2 to 100 kg. The design could also be scaled up to accommodate even larger spacecraft. As more data is collected from the CanX-7 mission, the deorbit model for spacecraft equipped with the drag sail device will be refined. With this model, it will be easy to determine the number of sail modules needed to deorbit a particular spacecraft based on its mass, geometry and initial altitude.

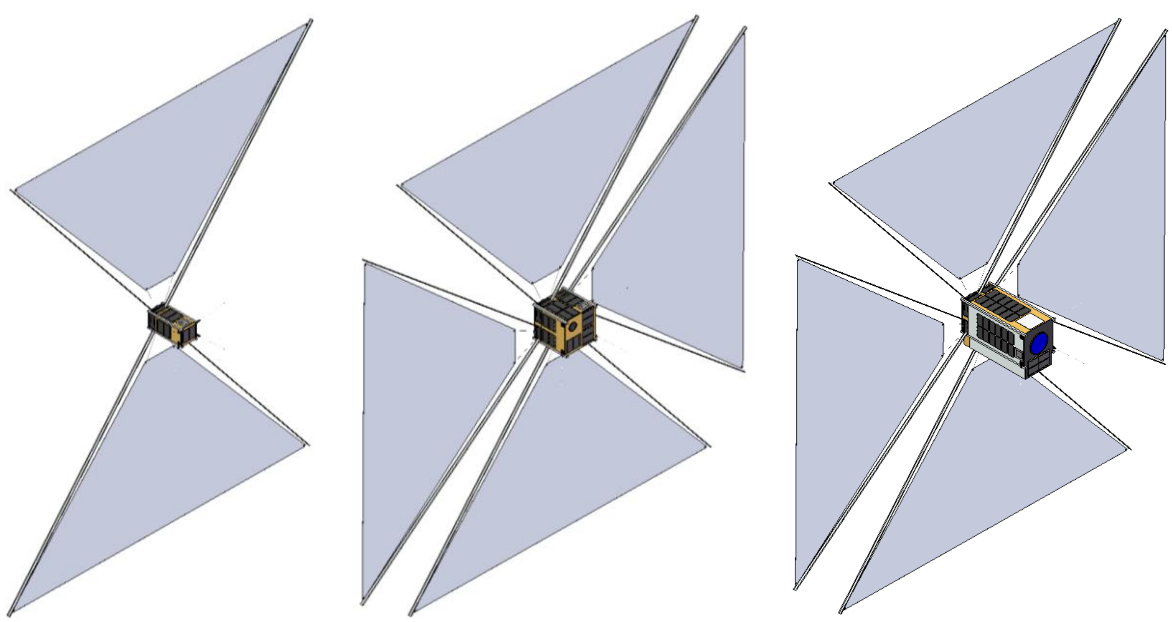

Figure 8: Drag Sail Concepts for a Variety of Spacecraft Geometries: 2U (left), SFL GNB Class (middle), SFL NEMO class (right)

Acknowledgments

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